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Aerosol Observations from Satellites: Brief Theory & Existing Products

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Monday, November 14, 2016
2nd International Smoke Symposium
Long Beach, CA, USA

Objectives

1. Gain a basic understanding of aerosol optical depth

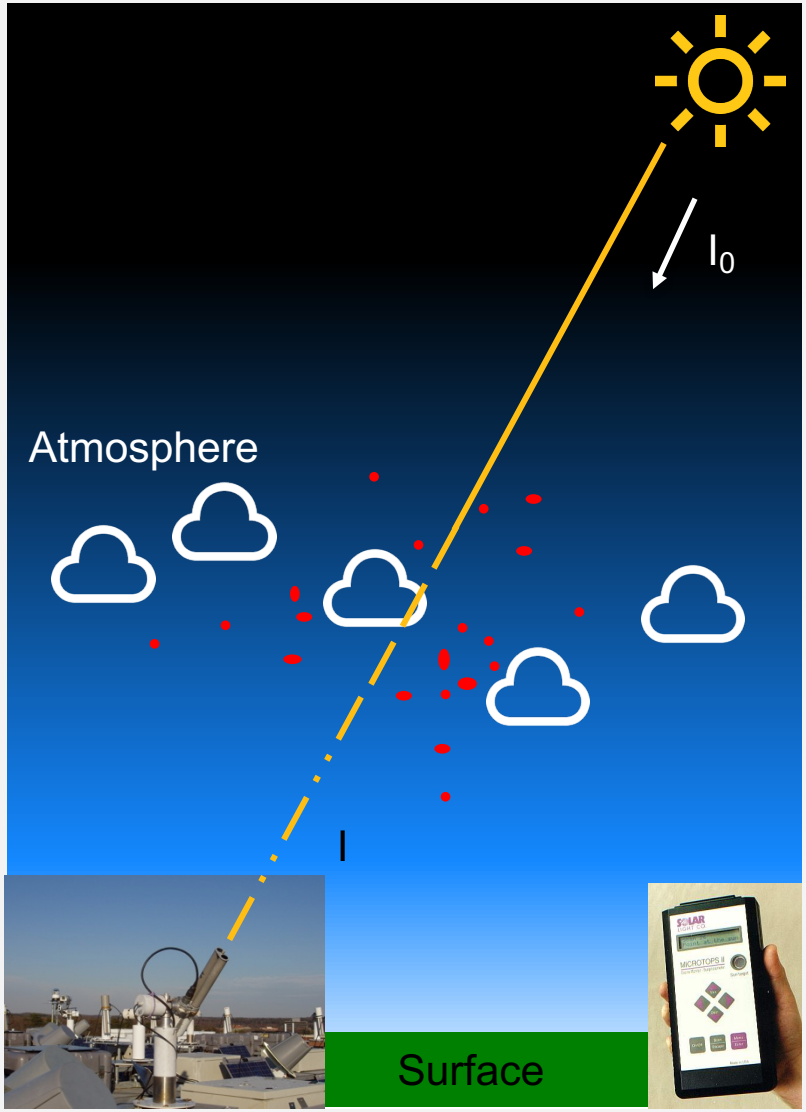
2. Gain knowledge of and ability to access available aerosol products from NASA sensors

Aerosol Optical Depth

- AOD: Aerosol **Optical** Depth
- AOT: Aerosol **Optical** Thickness

- These **optical measurements** of light extinction are used to represent aerosol amounts in the entire column of the atmosphere

Optical Depth



The optical depth expresses the quantity of light removed from a beam by **scattering** or **absorption** during its path through a **medium**.

optical depth τ as

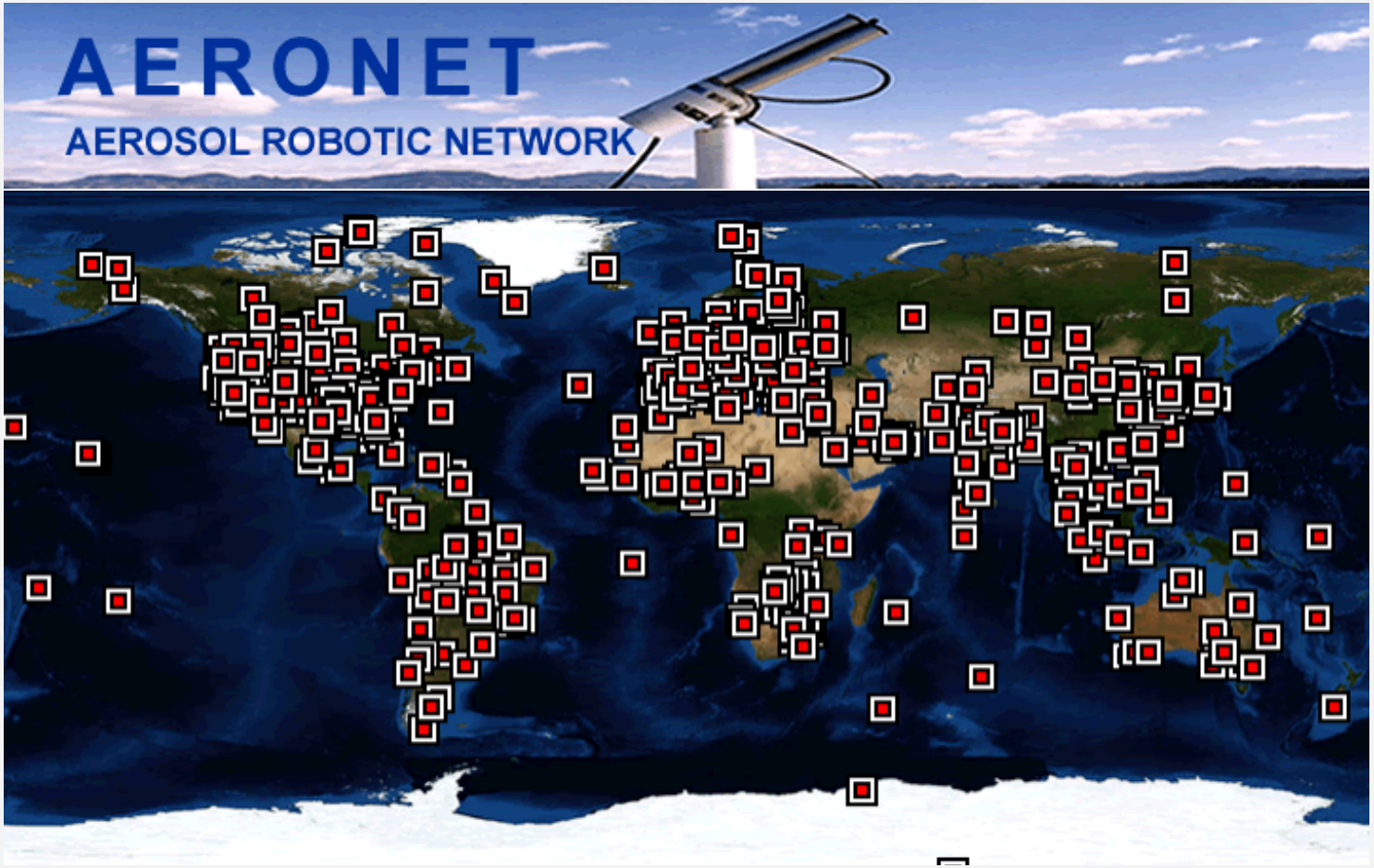
$$I = I_0 e^{-m\tau}$$

$$m = \sec\theta_0$$

$$\tau = \tau_{Rayl} + \tau_{aer} + \tau_{gas}$$

AERONET

http://aeronet.gsfc.nasa.gov/



Serves as a validation tool for satellite aerosol products

Satellites for Air Quality Data

- MODIS (Terra and Aqua)
  - AOD: columnar aerosol loading – can be used to get PM2.5 or PM10
- MISR (Terra)
  - Columnar aerosol loading in different particle size bins
  - In some cases aerosol heights
- OMI (Aura)
  - Absorbing aerosols, total aerosols
  - Trace gases
- VIIRS (NPP)
  - Aerosol optical depth
  - Aerosol type

Instrument Capabilities for Air Quality

Sensor Measurement Resolution

MODIS	250 m – 1 km
MISR	275 m – 1.1 km
OMI	13 x 24 km
VIIRS	750 m

Satellite Aerosol Products

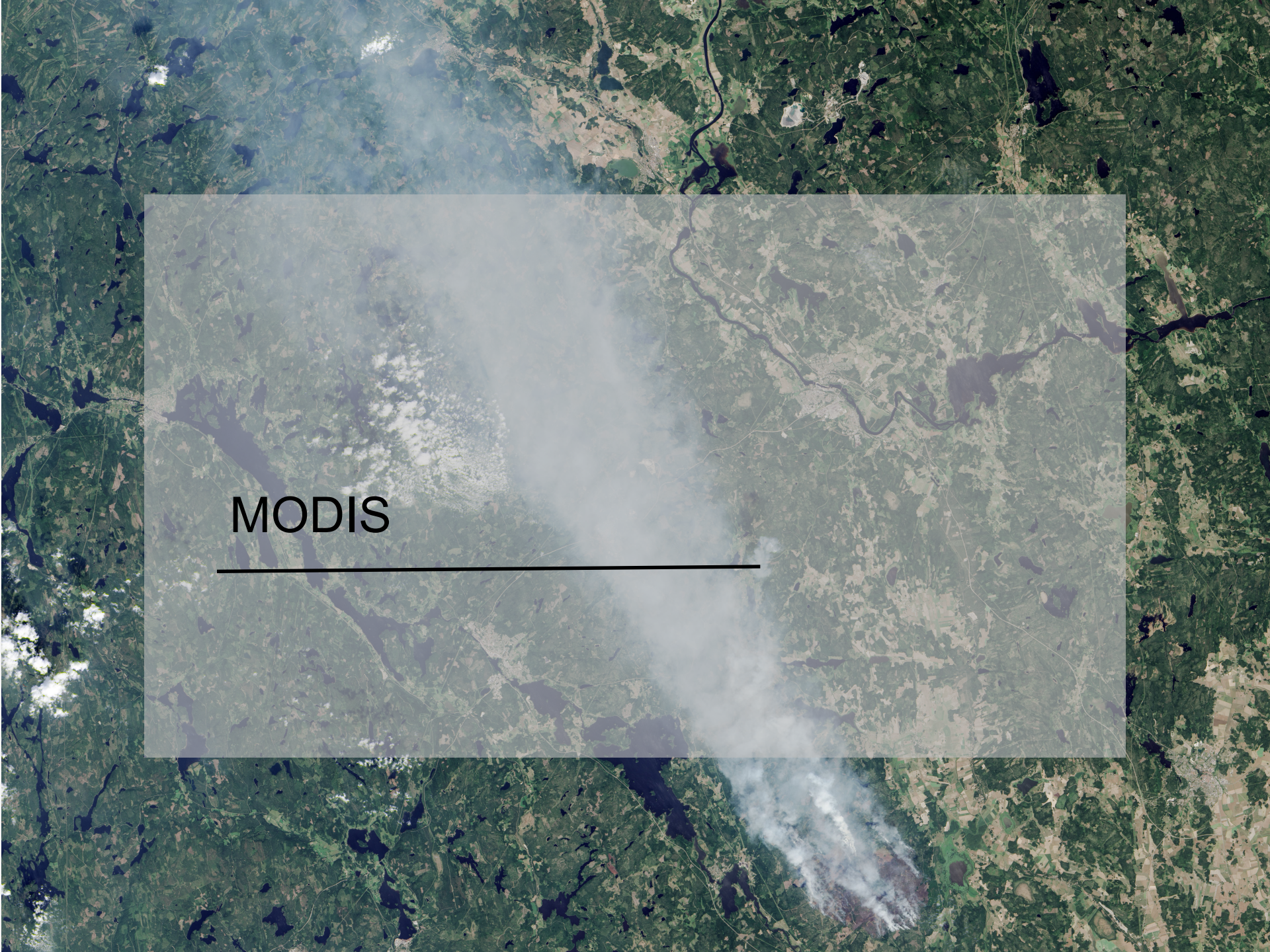
	MODIS	MISR	OMI	VIIRS
Strengths	Coverage Resolution Calibration Accuracy	Calibration Accuracy Particle shape Aerosol height for thick layer or plume	Indication of absorbing or scattering particles	Coverage Resolution Calibration Smaller bow-tie effect
Weaknesses	Bright Surfaces* Ocean glint Non-spherical particles	Coverage	Resolution Cloud contamination	Bright Surfaces* Ocean glint
Main Products	AOD Ocean–5 wavelengths Land–3 wavelengths Fine Fraction (Ocean only)	AOD 4 wavelengths Spherical/Non-spherical ratio Particle Size (3 Bins)	AOD AAOD Aerosol Index	AOD Aerosol Type
Product Resolution (level 2 and at Nadir)	10 Km 3 Km	17.6 Km	13 X 24 Km	0.75 km 6 km
Product Levels	2	2	2	2
Global Level 3 Aggregates	Daily 8 Day 30 Day	Monthly 3 Month Annual	Daily Monthly	Daily Monthly

Satellite Aerosol Products

	MODIS	MISR	OMI	VIIRS
Strengths	• Coverage • Resolution • Calibration • Accuracy	• Calibration • Accuracy • Particle shape • Aerosol height for thick layer or plume	Indication of absorbing or scattering particles	• Coverage • Resolution • Calibration • Smaller bow-tie effect
Weaknesses	• Bright Surfaces* • Ocean glint • Non-spherical particles	Coverage	• Resolution • Cloud contamination	• Bright surface* • Ocean glint

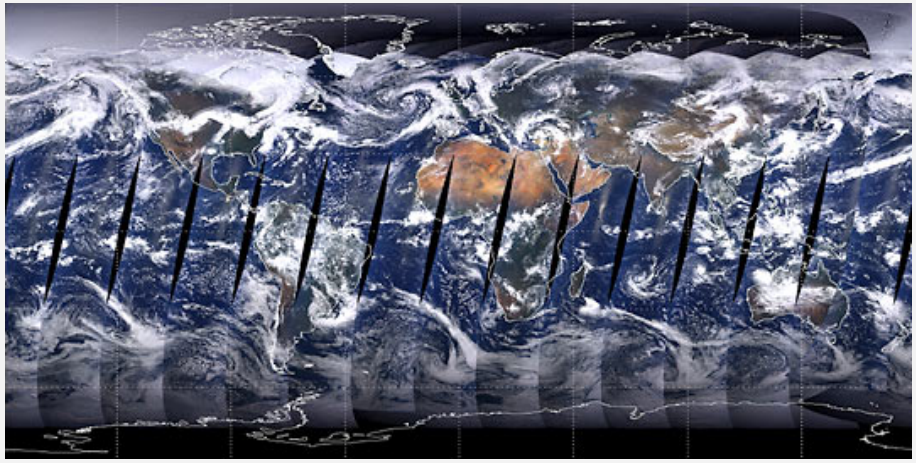
Satellite Aerosol Products

	MODIS	MISR	OMI	VIIRS
Main Products	• AOD • Ocean-5 wavelengths • Land-3 wavelengths • Fine Fraction (Ocean only)	• AOD • 4 wavelength • Spherical/Non-spherical ratio • Particle Size (3 bins)	• AOD • AAOD • Aerosol Index	• AOD • Aerosol Type
Product Resolution (Level 2 & at Nadir)	• 10 km • 3 km	17.8 km	13 x 24 km	• 0.75 km • 6 km
Product Levels	2	2	2	2
Global Level 3 Aggregates	• Daily • 8 day • 30 day	• Monthly • 3 month • Annual	• Daily • Monthly	• Daily • Monthly


MODIS

Moderate Resolution Imaging Spectroradiometer

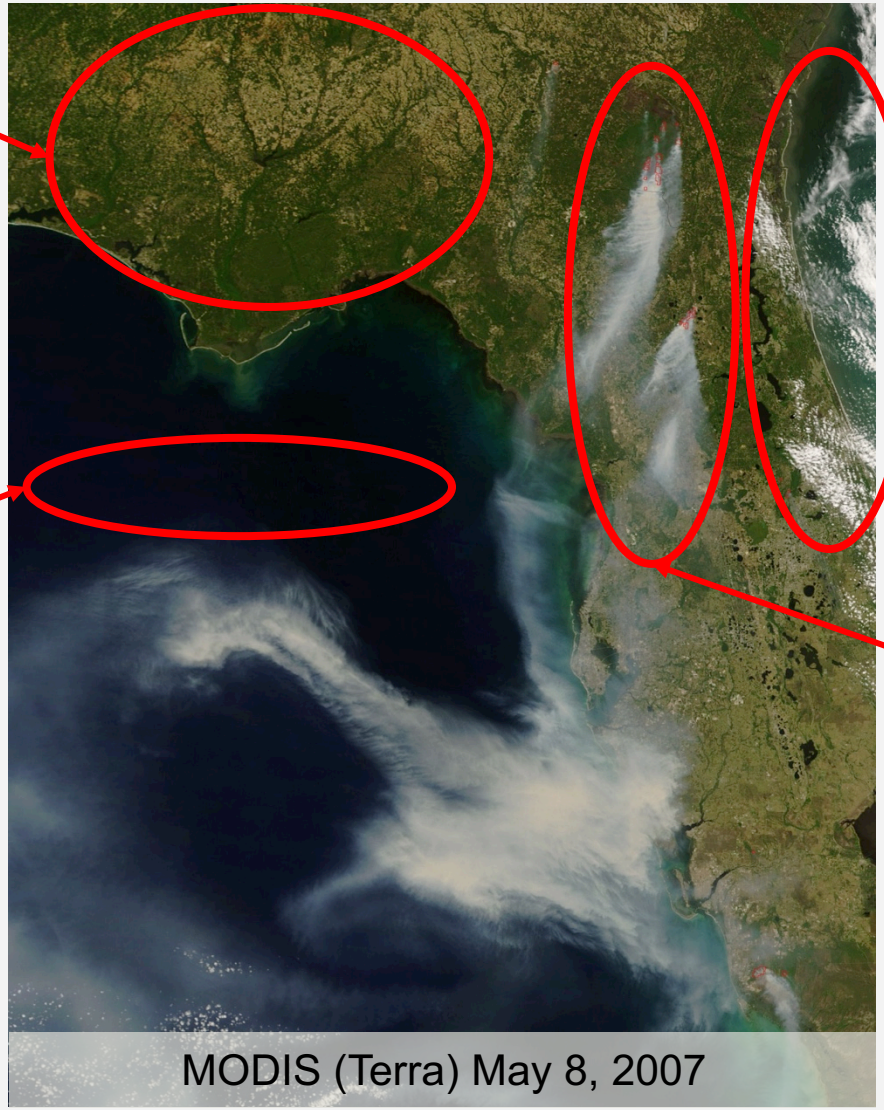
MODIS



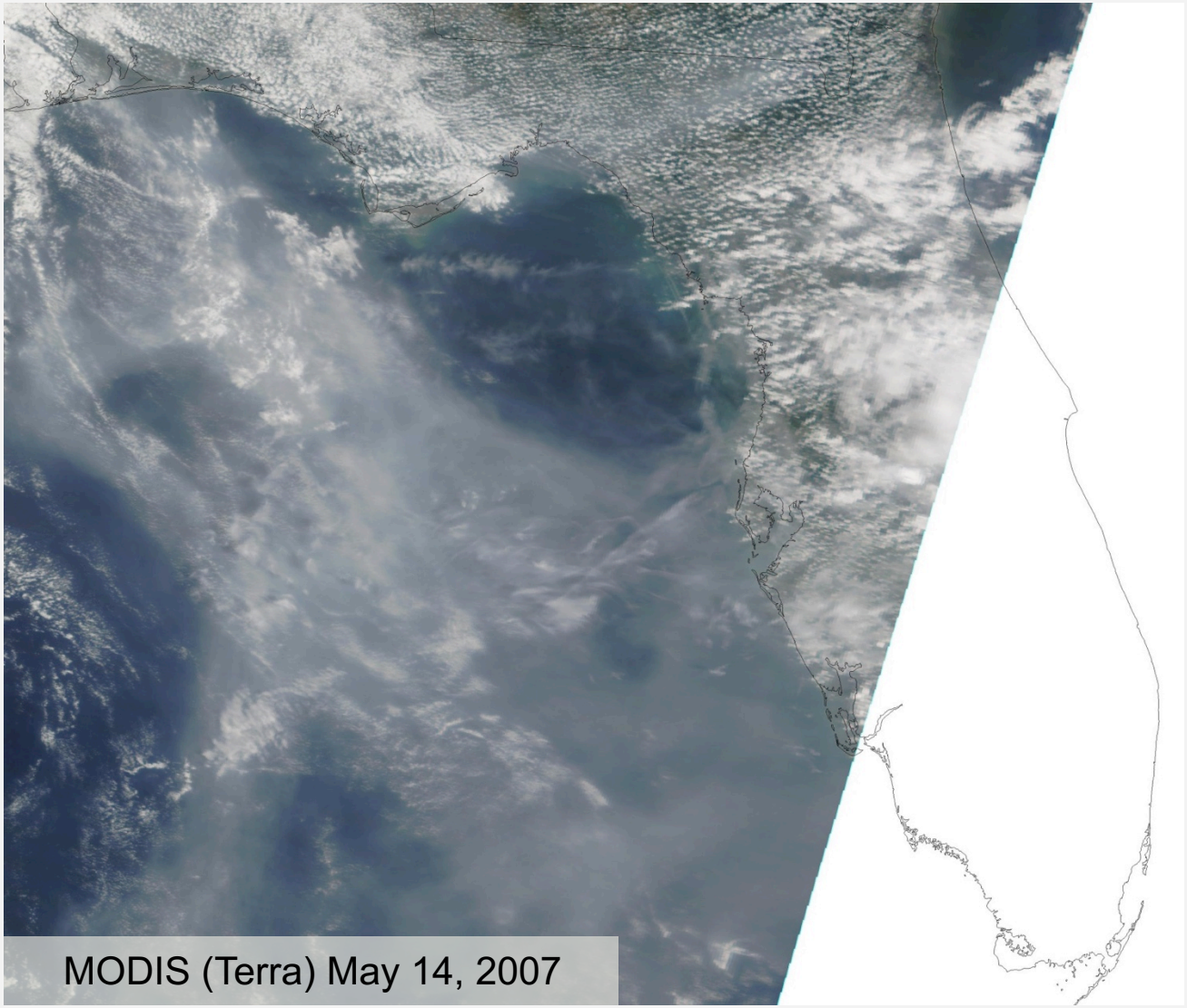
- **Spatial Resolution**
  - 250m, 500m, 1km
- **Platform**
  - Terra & Aqua
- **Temporal Resolution**
  - 2000-present
  - Daily, 8-day, 16-day, monthly, quarterly, yearly
- **Data Format**
  - Hierarchal Data Format – Earth Observing System Format (HDF-EOS)
- **Spectral Coverage**
  - 36 bands (major bands include red, blue, IR, NIR, MIR)
    - Bands 1-2: 250m
    - Bands 3-7: 500m
    - Bands 8-36: 1,000m


Aerosol Retrieval

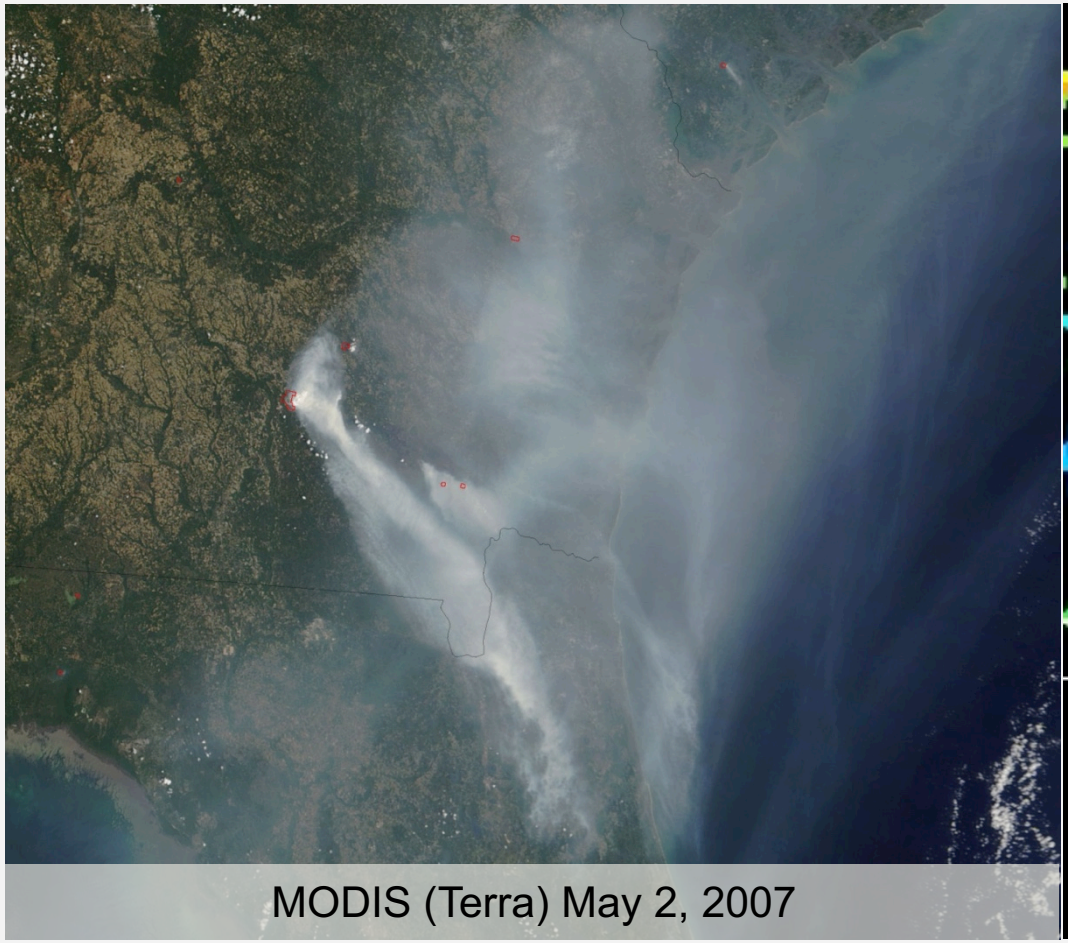
Aerosol Detection



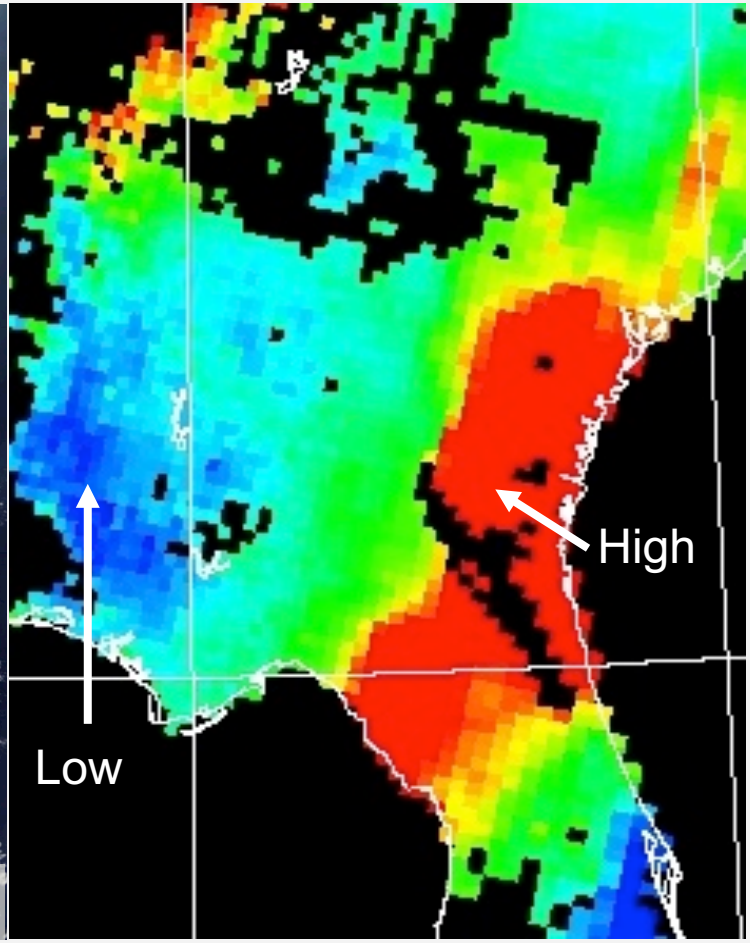
Complex Image: Smoke & Clouds



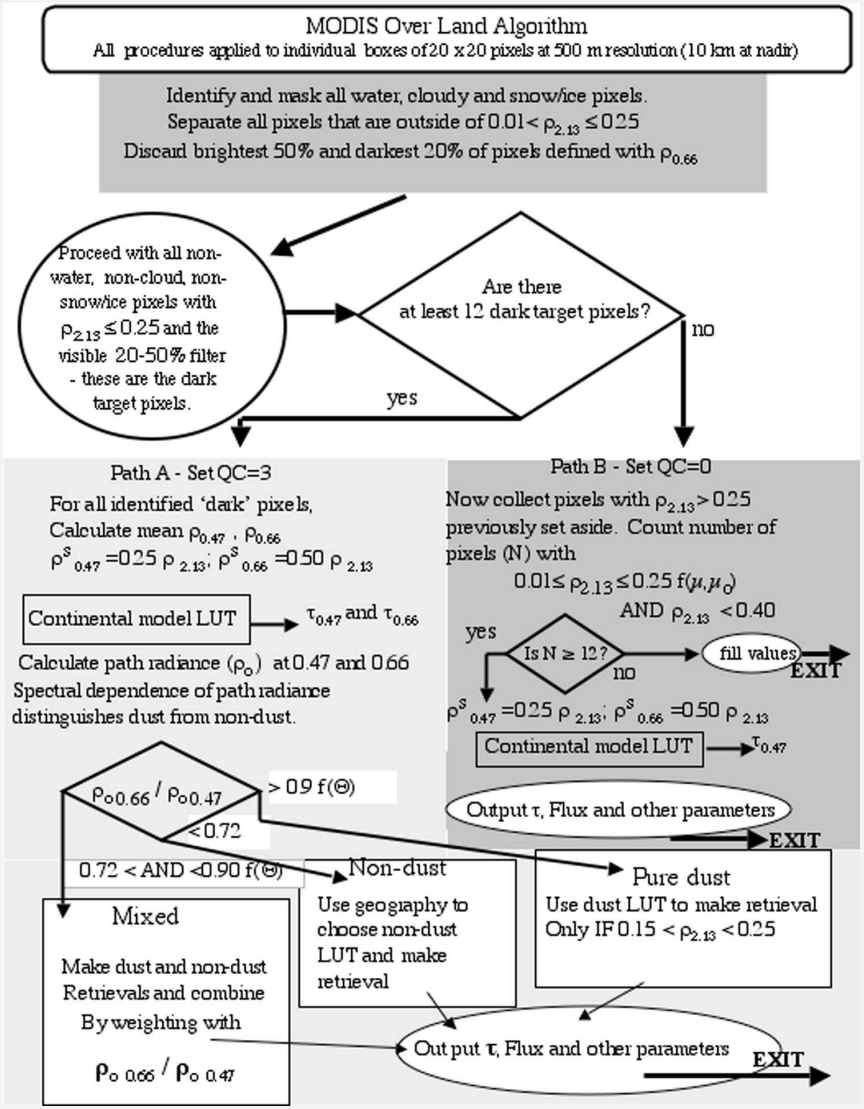
Radiance to Aerosol Products



MODIS (Terra) May 2, 2007



Aerosol Retrieval Algorithm



Aerosol retrieval algorithm is a complex inversion scheme where assumptions are made in simulating satellite observations with advance radiative transfer calculations to retrieve atmospheric aerosol properties

Sources: Remer et al., 2005, Levy et al., 2013

Data Product Hierarchy

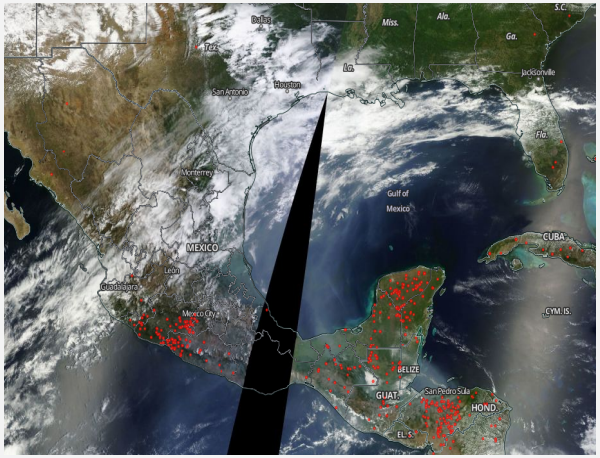
- Raw data with and without applied calibration
- No aerosol data

- Geophysical products
- Aerosol data

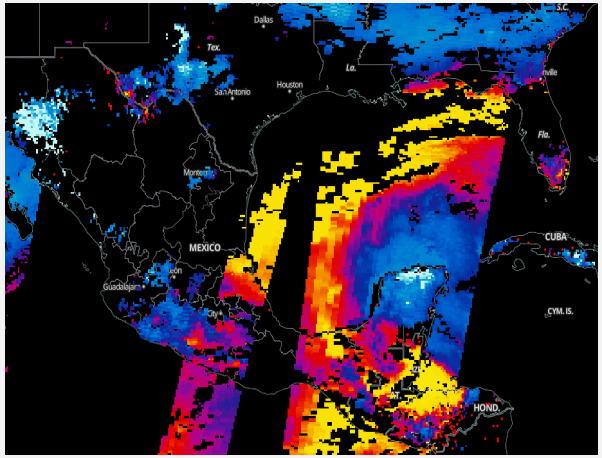
- Globally gridded geophysical products
- Aerosol data

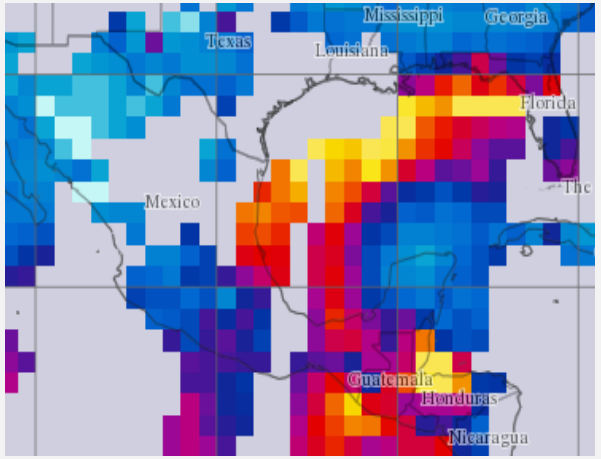
Levels of Data

RGB



Aerosol Optical Depth





Level 1B
Calibration to Radiance

Level 2
Aerosol Retrieval Algorithm

Level 3
Spatial & Temporal Averaging

MODIS Products

MOD01 Level-1A Radiance Counts

MOD02 Level-1B Calibrated Geolocated Radiances – also Level 1B"subsampled" 5kmx5km pro

MOD03 Geolocation Data Set

MOD04 Aerosol Product

MOD05 Total Precipitable Water

MOD06 Cloud Products

MOD07 Atmospheric Profiles

MOD08 Gridded Atmospheric Product (Level 3)

MOD09 Atmospherically-corrected Surface Reflectance

MOD10 Snow Cover

MOD11 Land Surface Temperature & Emissivity

MOD12 Land Cover/Land Cover Change

MOD13 Vegetation Indices

MOD14 Thermal Anomalies, Fires & Biomass Burning

MOD15 Leaf Area Index & FPAR

MOD16 Surface Resistance & Evapotranspiration

MOD17 Vegetation Production, Net Primary Productivity

MOD18 *Normalized Water-leaving Radiance

MOD19 Pigment Concentration

MOD20 Chlorophyll Fluorescence

MOD21 *Chlorophyll_a Pigment Concentration

MOD22 Photosynthetically Active Radiation (PAR)

MOD23 Suspended-Solids, Conc, Ocean Water

MOD24 Organic Matter Concentration

MOD25 Coccolith Concentration

MOD26 *Ocean Water Attenuation Coefficient

MOD27 Ocean Primary Productivity

MOD28 *Sea Surface Temperature

MOD29 Sea Ice Cover

MOD32 Processing Framework & Match-up Database

MOD33 Gridded Snow Cover

MOD34 Gridded Vegetation Indices

MOD35 Cloud Mask

MOD36 Total Absorption Coefficient

***MOD37 Ocean Aerosol Optical Thickness**

MOD39 Clear Water Epsilon

MOD43 Albedo 16-day L3

MOD44 Vegetation Cover Conversion

MYD – MODIS Aqua
MOD – MODIS Terra

A Few More Things About MODIS Data…

- MOD: Terra product
- MYD: Aqua product

- All MODIS products come in **HDF** format
- In HDF format each file contains both data and metadata
- **Scientific Data Set (SDS)**: each parameter within a MODIS HDF file is referred to as an SDS
  - SDS must be referenced precisely according to name when analyzing the data within your own computer code

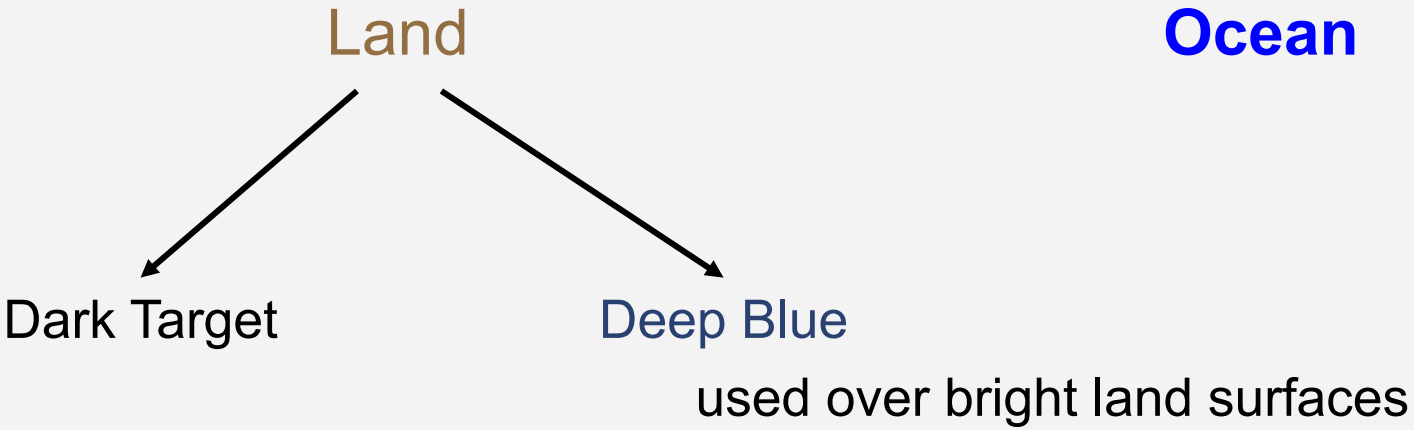
Things That Change with Each Instrument

(So you need to learn them!)

- Calibration Accuracy
- Quality Assurance – quality of the data
- Data Formats
- Product Resolutions
- Creating Level 3 products from Level 2 –temporally and spatially averaging
- Current data release and data history

MODIS Aerosol Products

Three Separate Algorithms

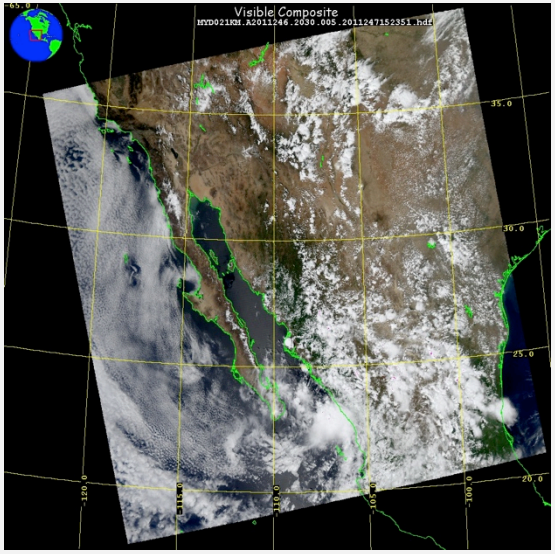


- The dark target and deep blue products are separate and when both are available, the user must select which to use

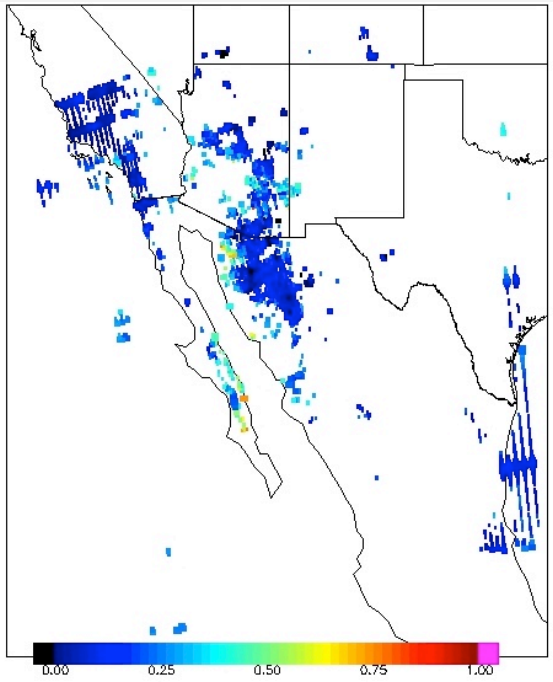
- In collection 6, there is a joint product that uses an automated procedure to select the appropriate product

MODIS Aerosol Products

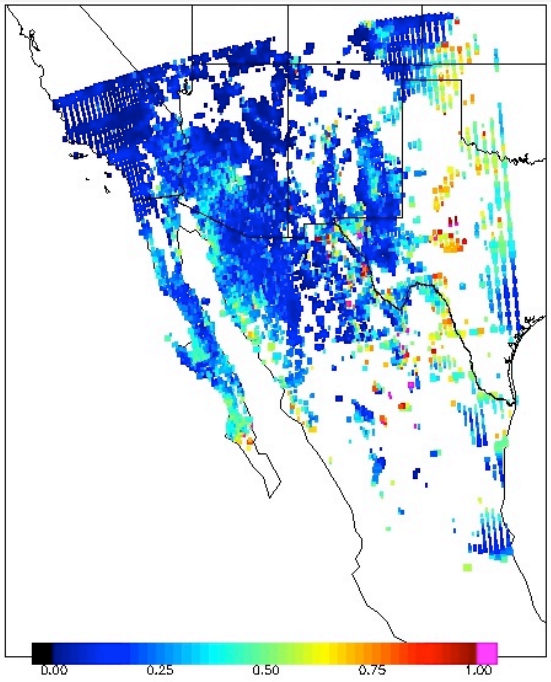
Two Algorithms



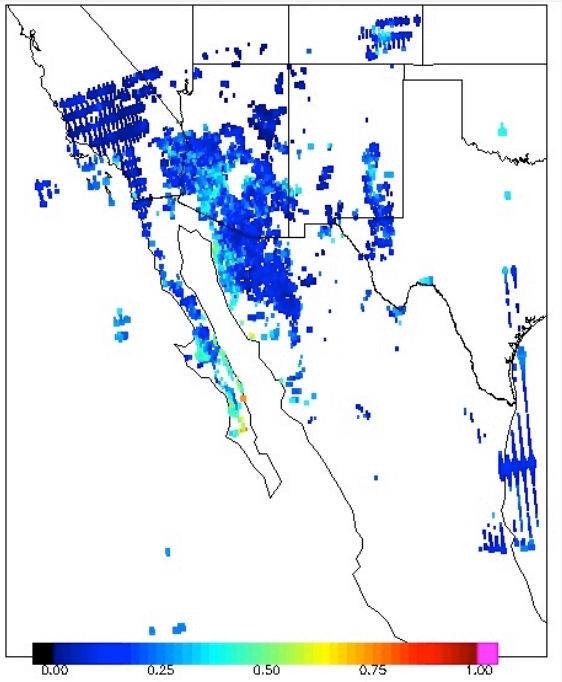
Dark Target



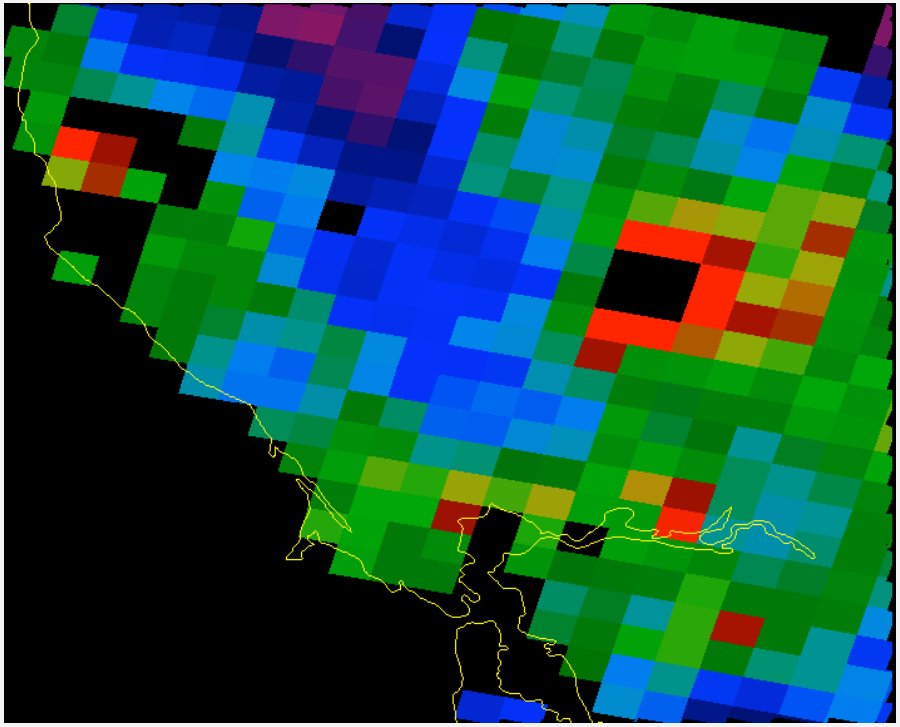
Deep Blue

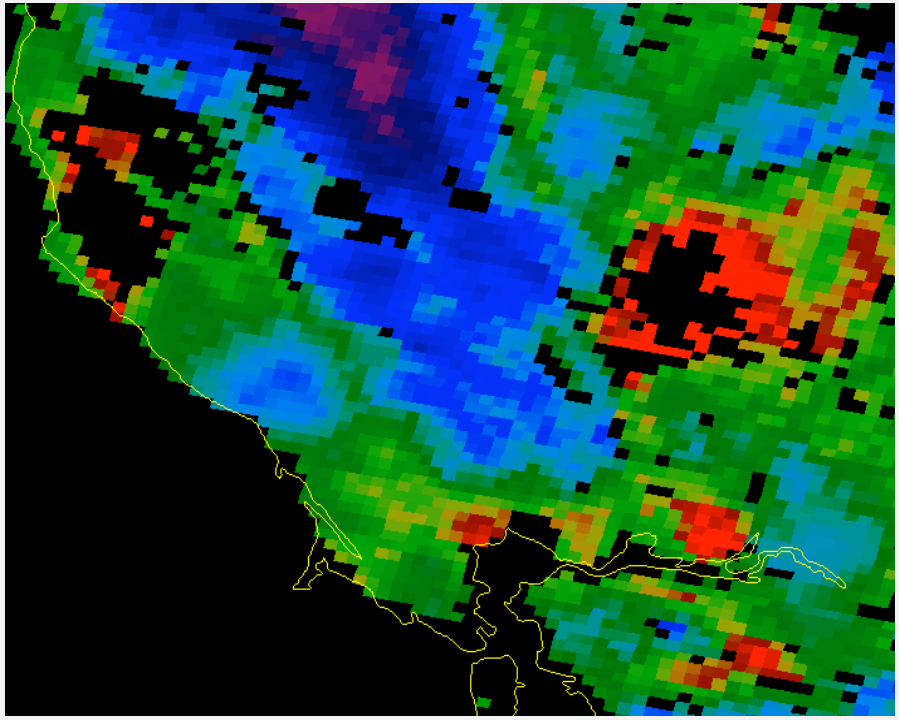


Deep_Dark_Combined



MODIS 10 km vs. 3 km Products





Quality Assurance is Extremely Important

QA indicates confidence in the quality of the retrieval

Quality_Assurance_Ocean

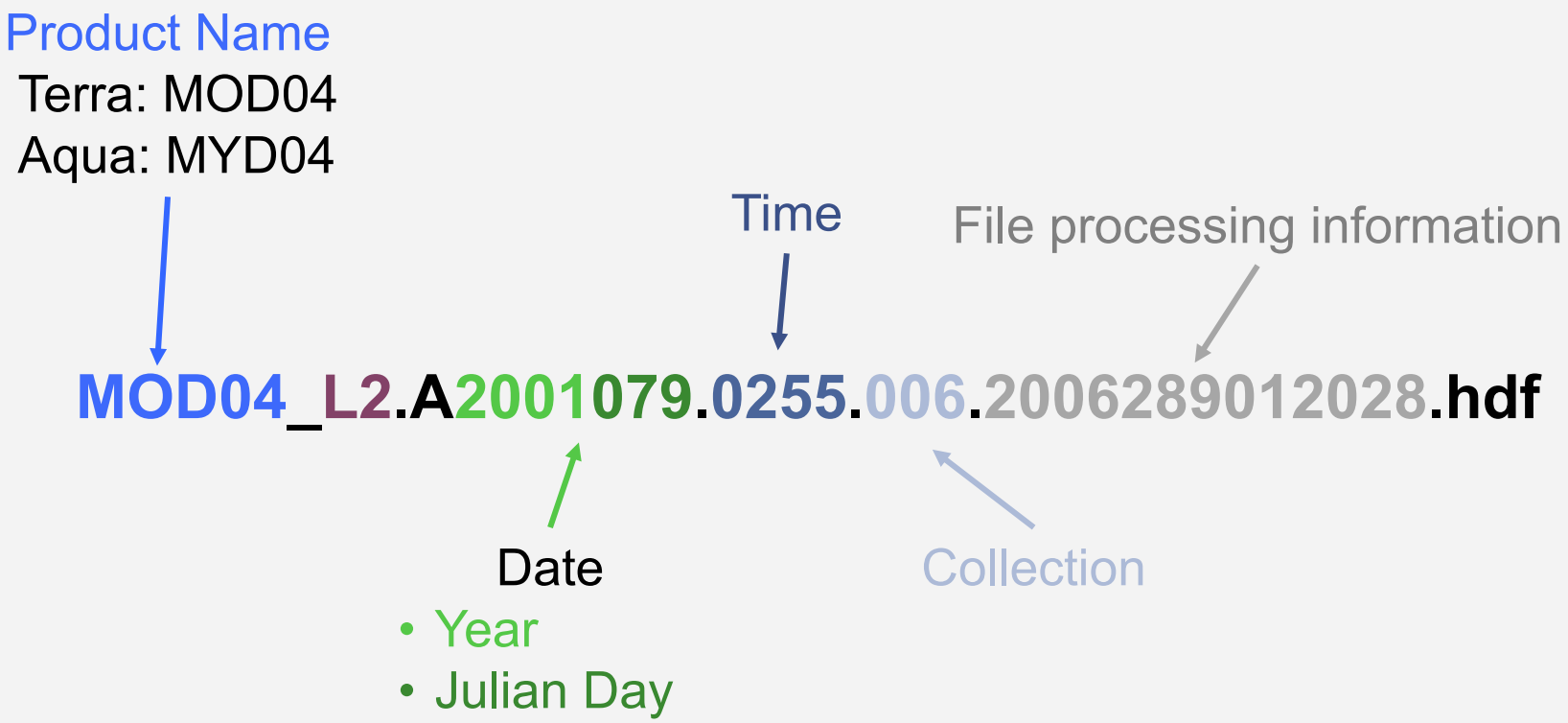
- Scale is 0-3
- Recommended Ocean QA above 1, 2, 3
- Factors:
  - Number of pixels
  - Error fitting
  - **How close to glint**

Quality_Assurance_Land

- Scale is 0-3
- Recommended Land QA of 3
- Factors:
  - Number of pixels
  - Error fitting
  - **Surface reflectance**

Understanding a MODIS File Name

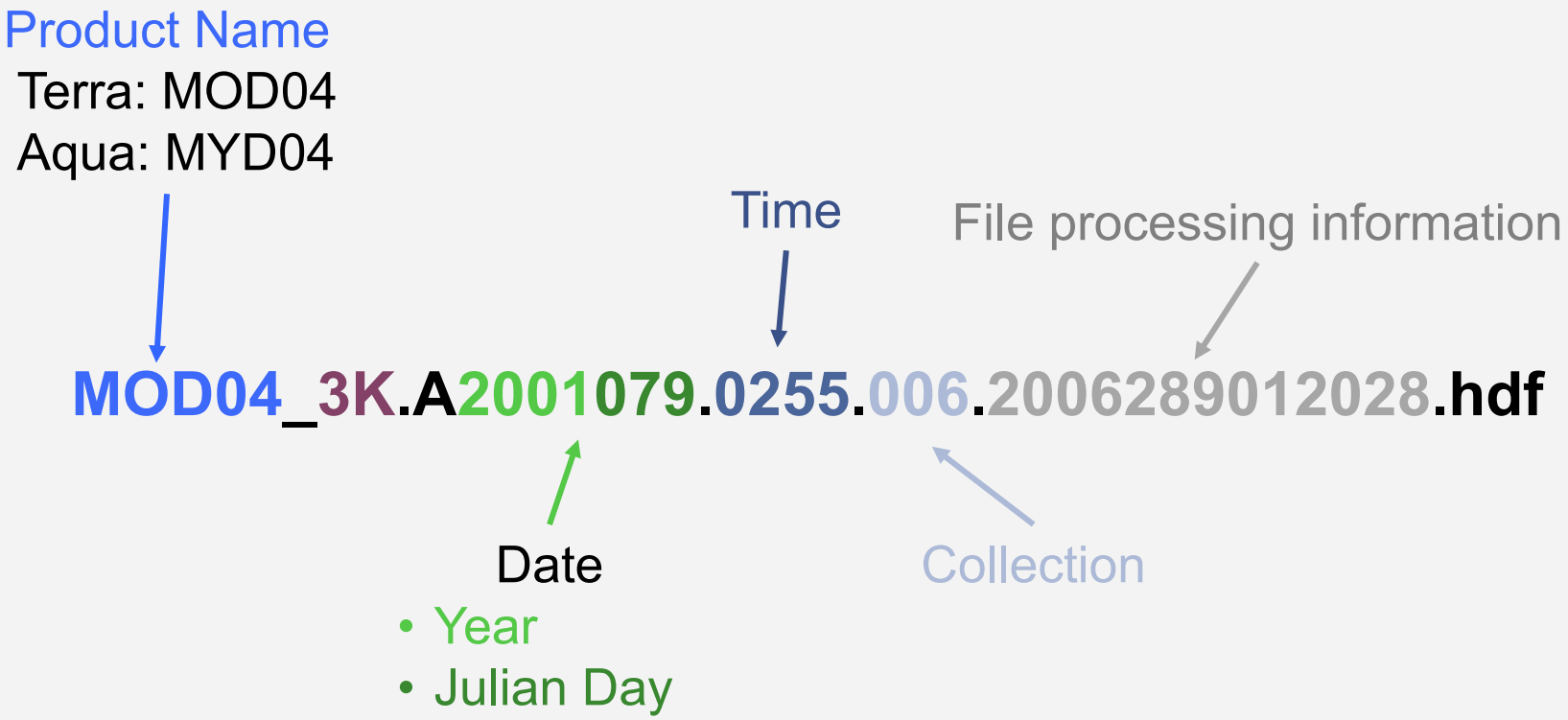
Level 2, 10 km, Aerosol Product



HDFLook, Panoply, IDL, Python, Fortran, MatLab, and more can be used to read the data

Understanding a MODIS File Name

Level 2, 3 km, Aerosol Product

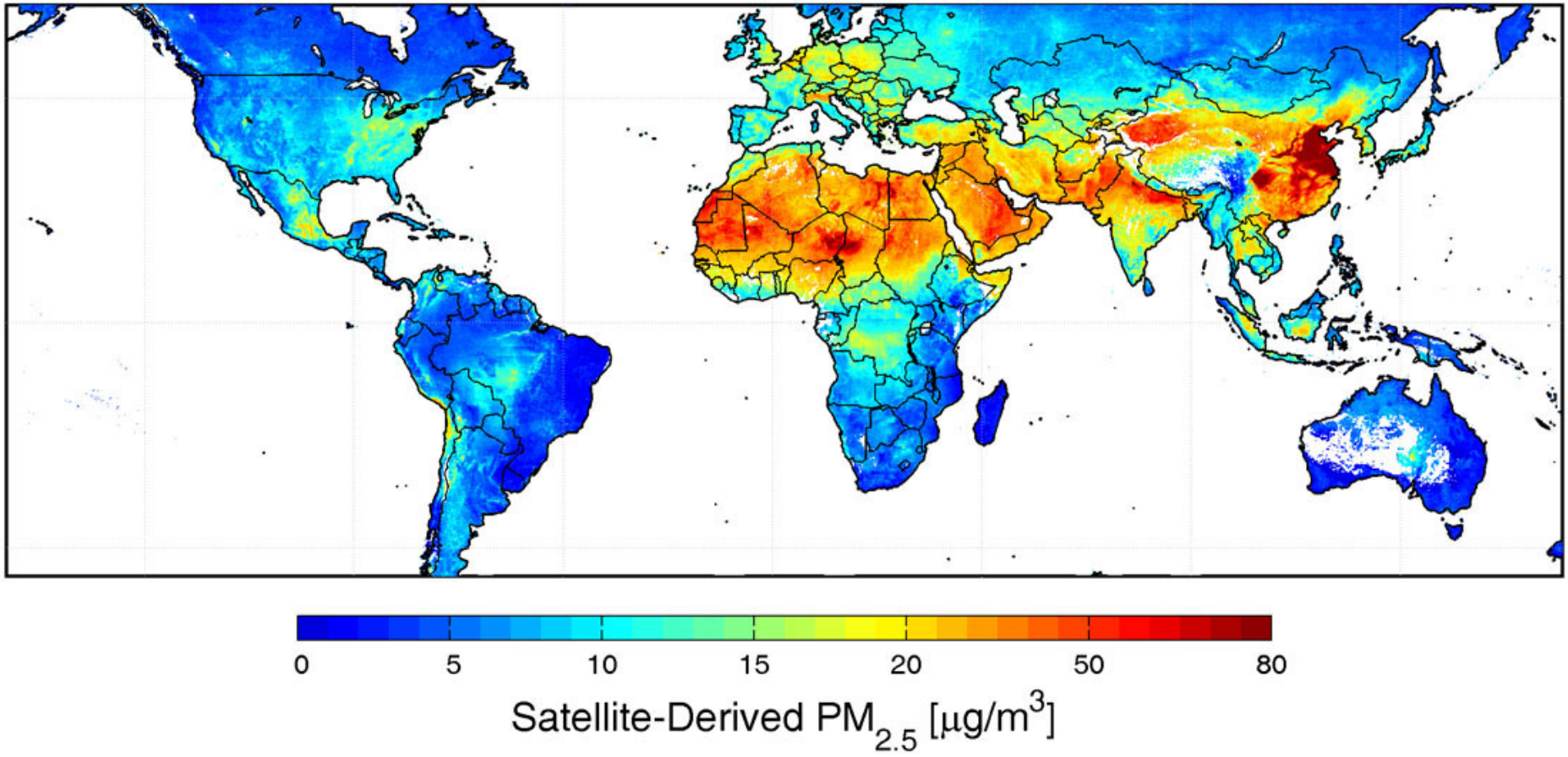


HDFLook, Panoply, IDL, Python, Fortran, MatLab, and more can be used to read the data

MODIS Aerosol Parameters (SDS)

- Optical_Depth_Land_and_Ocean
  - Retrieved using Dark Target Algorithm
  - Only high quality data
    - Over land QA = 3
    - Over ocean QA = 1, 2, 3
  - 10 km and 3km
- Dark_Target_Deep_Blue_Optical_Depth_550_Combined
  - Deep Blue & Dark Target Algorithm Merged Product
  - 10km only
- Dark_Target_Deep_Blue_Optical_Depth_550_Combined_QA
  - Quality flag associated with DD product

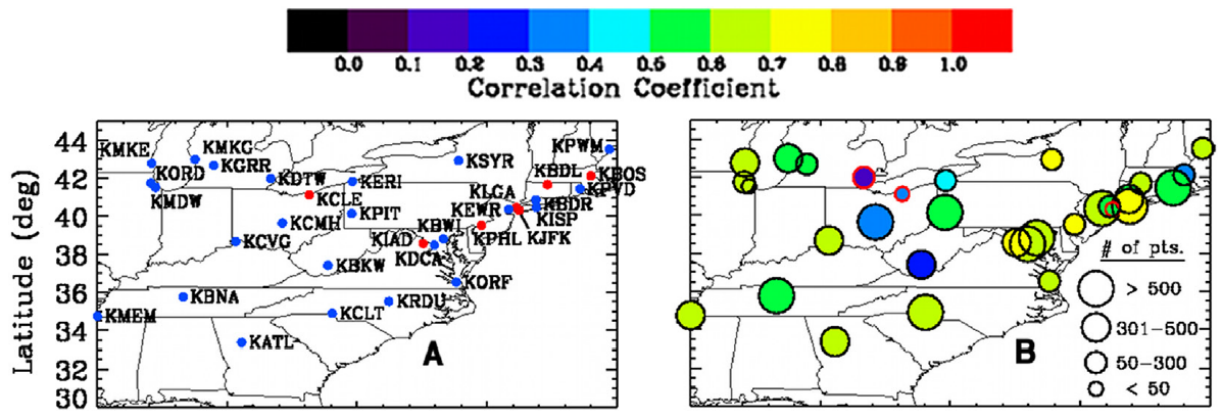
Application of MODIS Aerosol Product



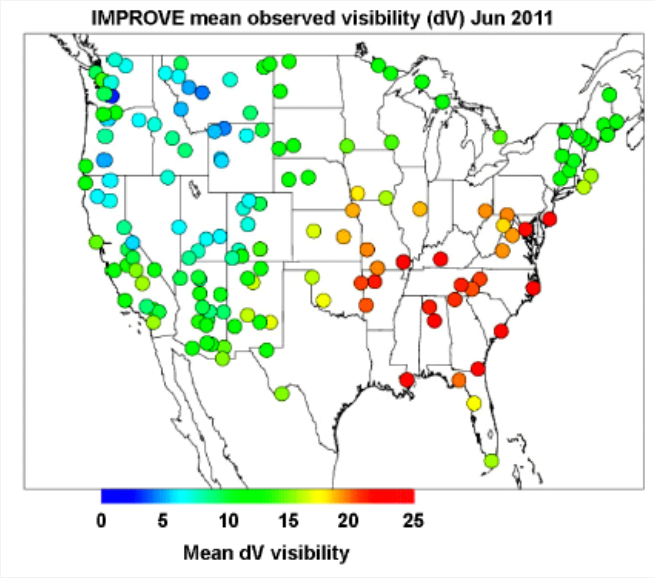
Source: van Donkelaar et al., 2006, 2009

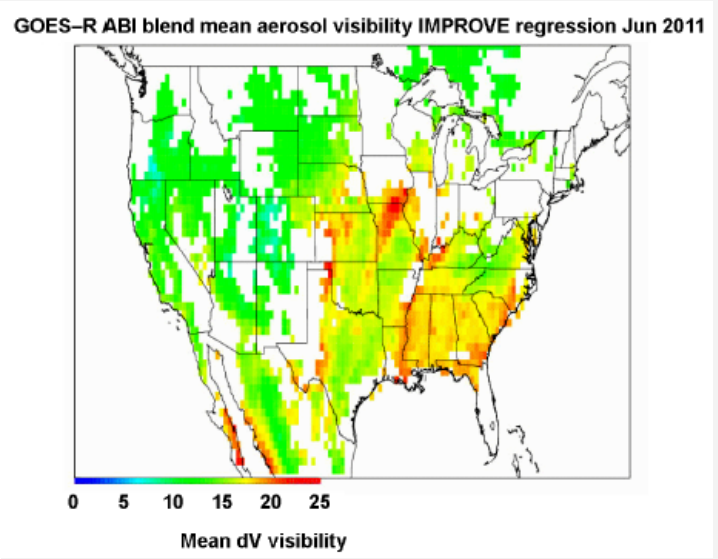
Application of Aerosol Product - Visibility

- Kessner et al., 2013
  - Visibility from MODIS AOD
  - Compared to ASOS



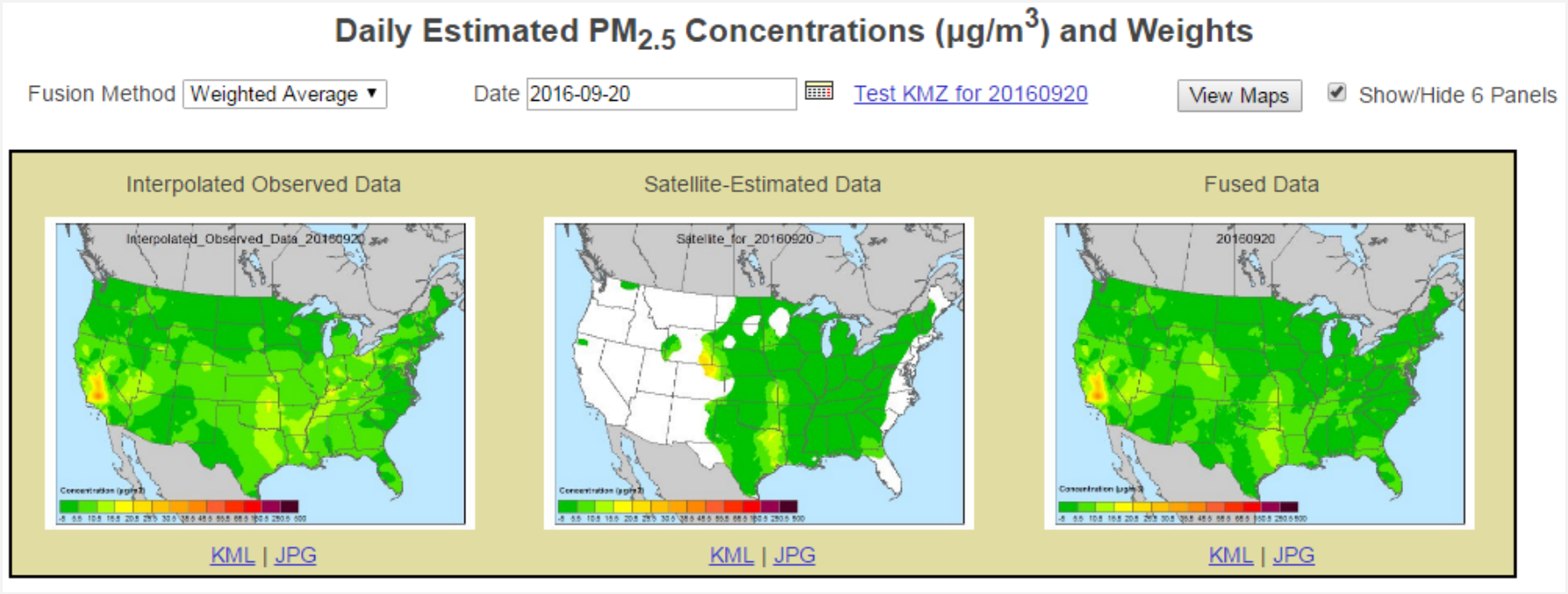
- Brunner et al., 2016
  - Visibility from GOES AOD
  - Compared to IMPROVE





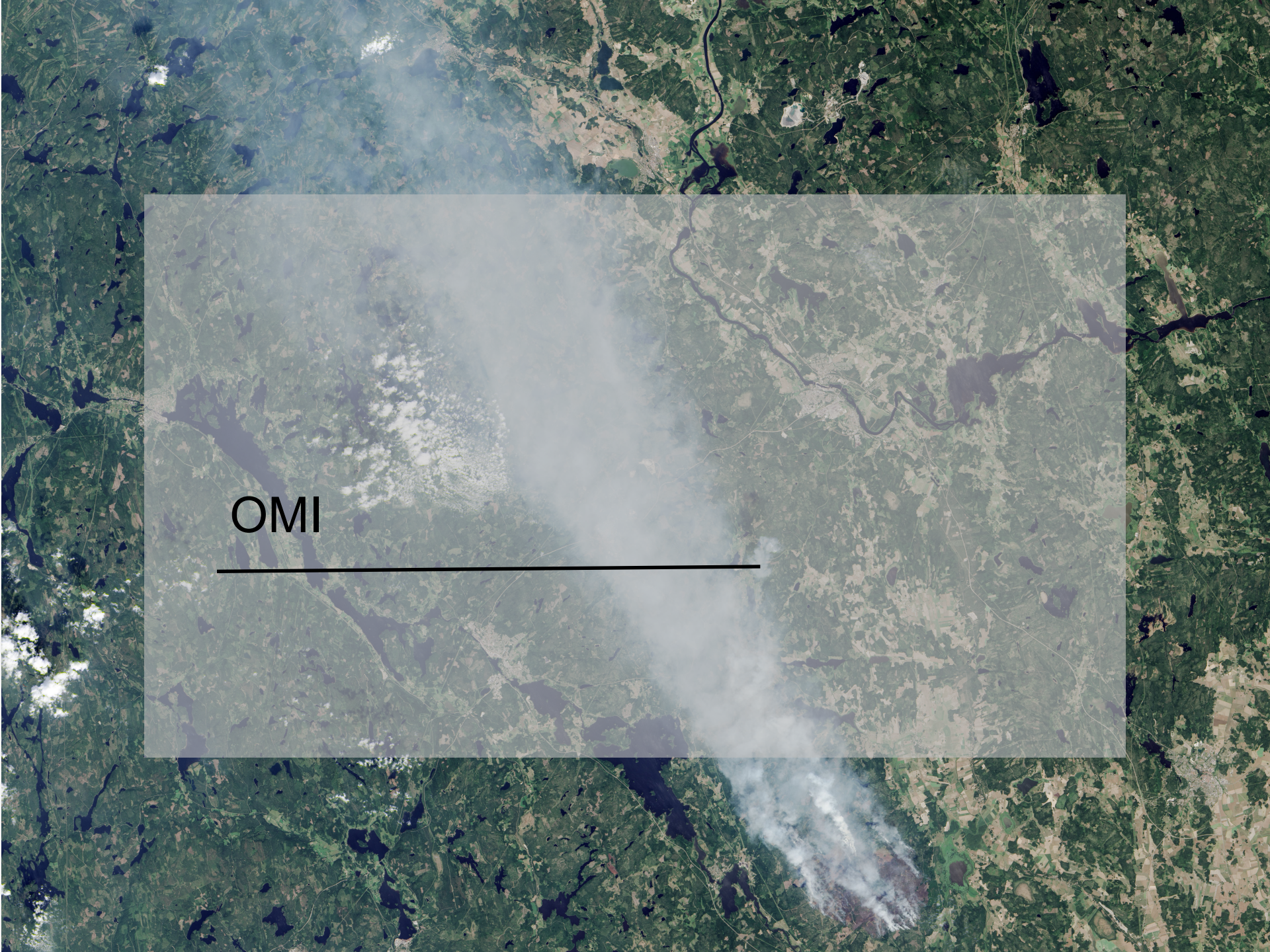
Application of MODIS Aerosol Product - Fusion

- AirNow Satellite Data Processor
  - https://youtu.be/ALPBWkBAxf4

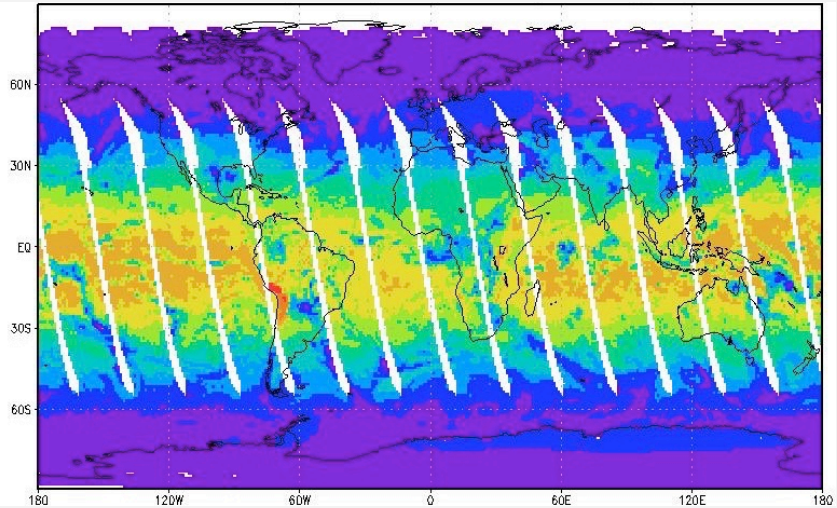


Access to MODIS Aerosol Products

- NASA LAADSWeb
  - Searchable database, FTP access
  - http://ladsweb.nascom.nasa.gov/index.html
- MODIS-Atmos Site
  - Complete RGB archive with Level 3 product imagery
  - http://modis-atmos.gsfc.nasa.gov/
- Giovanni for Level 3 data sets
  - Web tool for imagery visualization and analysis
  - http://disc.gsfc.nasa.gov/gesNews/giovanni_3_end_of_service?instance_id=MODIS_DAILY_L3
- Dark Target Algorithm Site
  - http://darktarget.gsfc.nasa.gov/
- Deep Blue Algorithm Site
  - http://deepblue.gsfc.nasa.gov/


OMI

Ozone Monitoring Instrument (OMI)



- One of four sensors on the EOS-Aura platform
  - OMI, MLS, TES, HIRDLS
- An international project
  - Holland, USA, Finland
- Launched July 15, 2004

Instrument Characteristics

- Nadir solar backscatter spectrometer
- Spectral Range: 270-500m
  - Resolution ~1nm
- Swath Width: 2,600km
  - Global daily coverage with 13x24 km spatial resolution

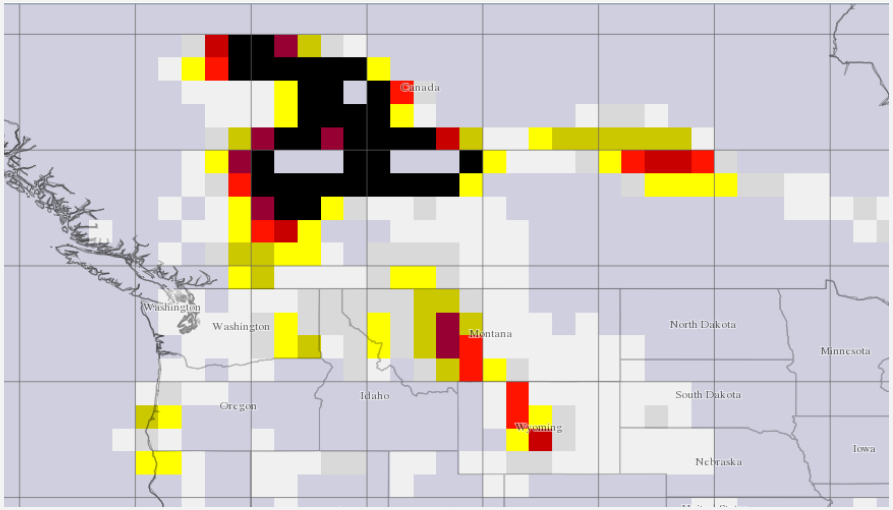
Retrieval Products

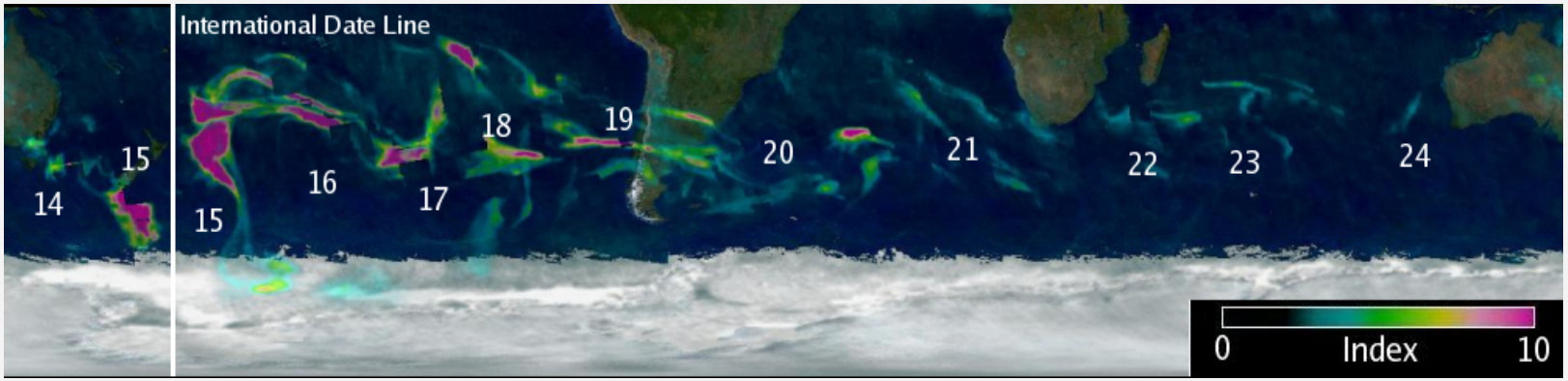
- Column Amounts
  - Ozone (O_3)
  - Nitrogen Dioxide (NO_2)
  - Sulfur Dioxide (SO_2)
  - Others
- Aerosols

Applications of the Aerosol Index

- Validation tool for transport models
- Separation of carbonaceous from sulfate aerosols
- Tracking of aerosol plumes above clouds and over ice and snow

Aerosols over clouds, April 14, 2006

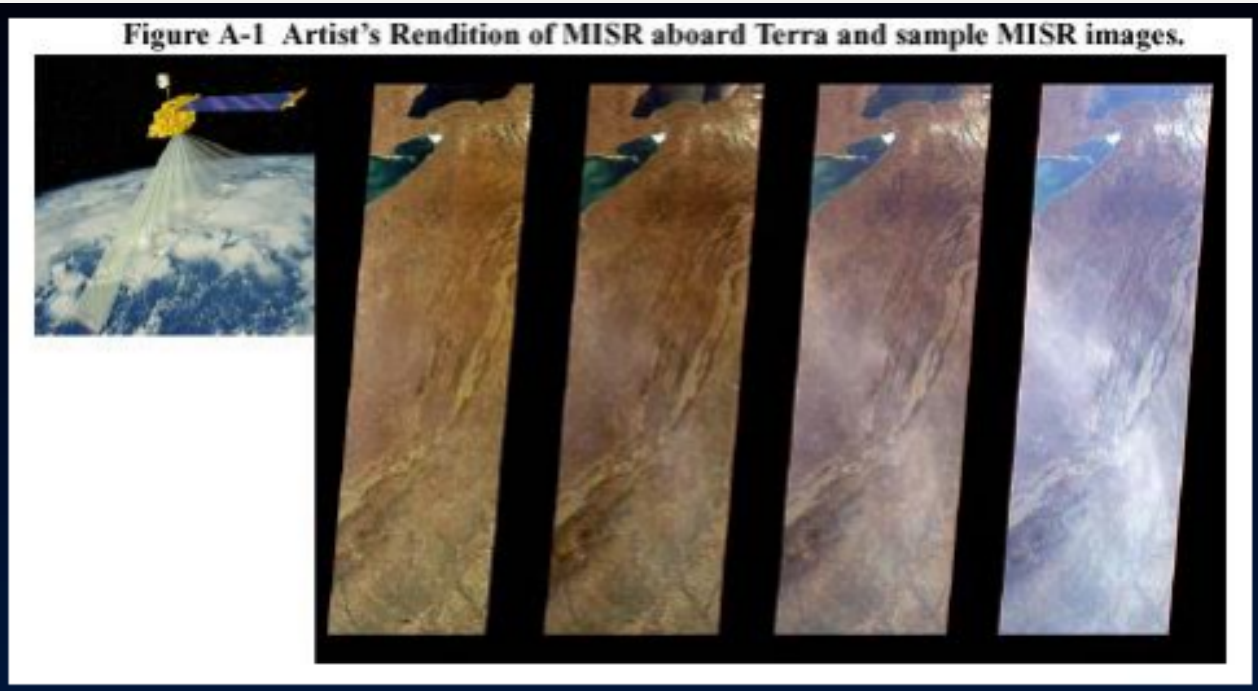




Above: Transport around the globe of a high altitude smoke layer generated by the Dec 2006 Australian fires. Numbers indicate the day of the month.


MISR

MISR Instrument

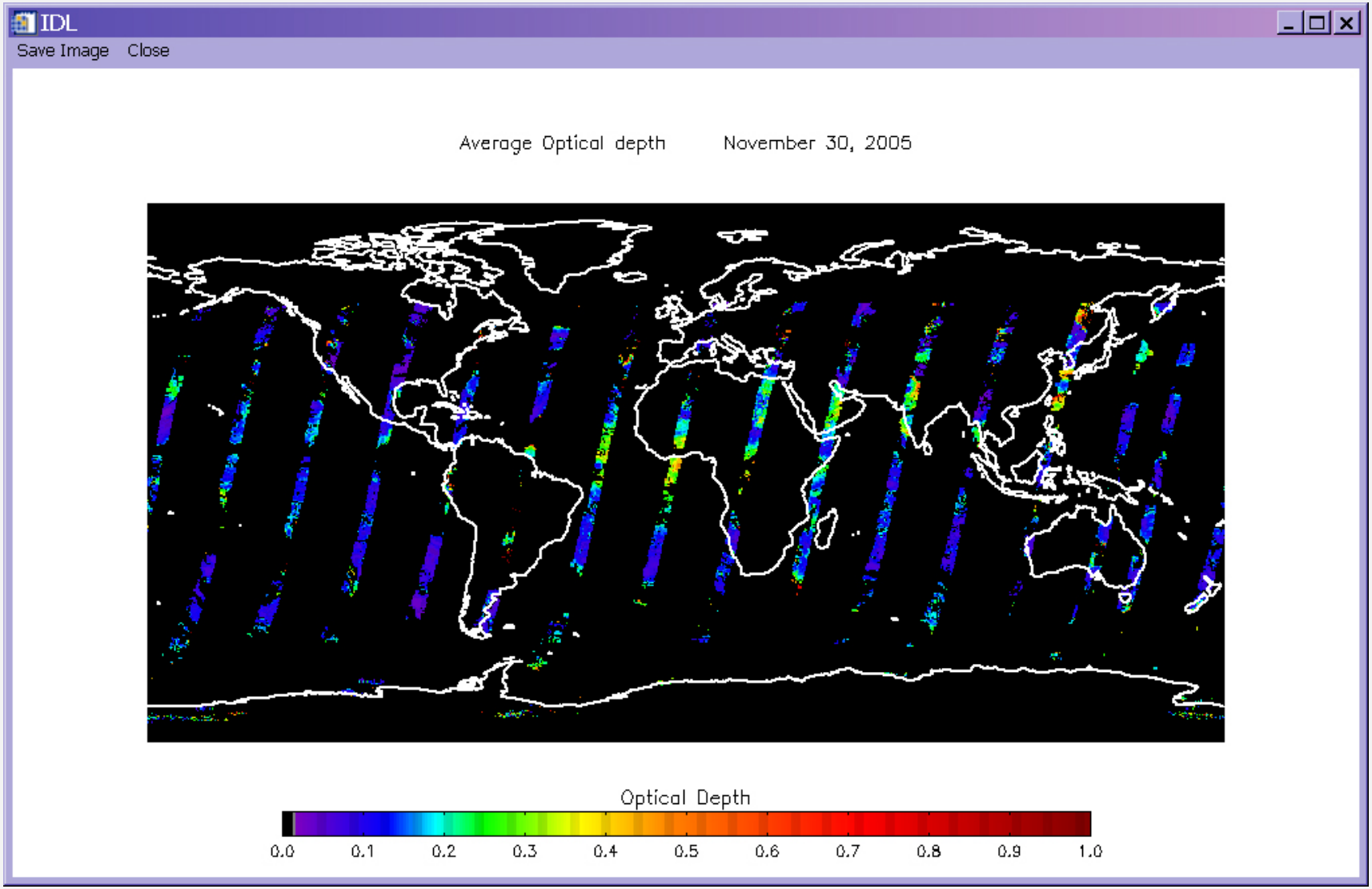


Source: Brian E. Rheingans, JPL

Four MISR images over Appalachain Mountains
Nadir, 45.6 deg, 60.0 deg, 70.5 deg forward viewing cameras

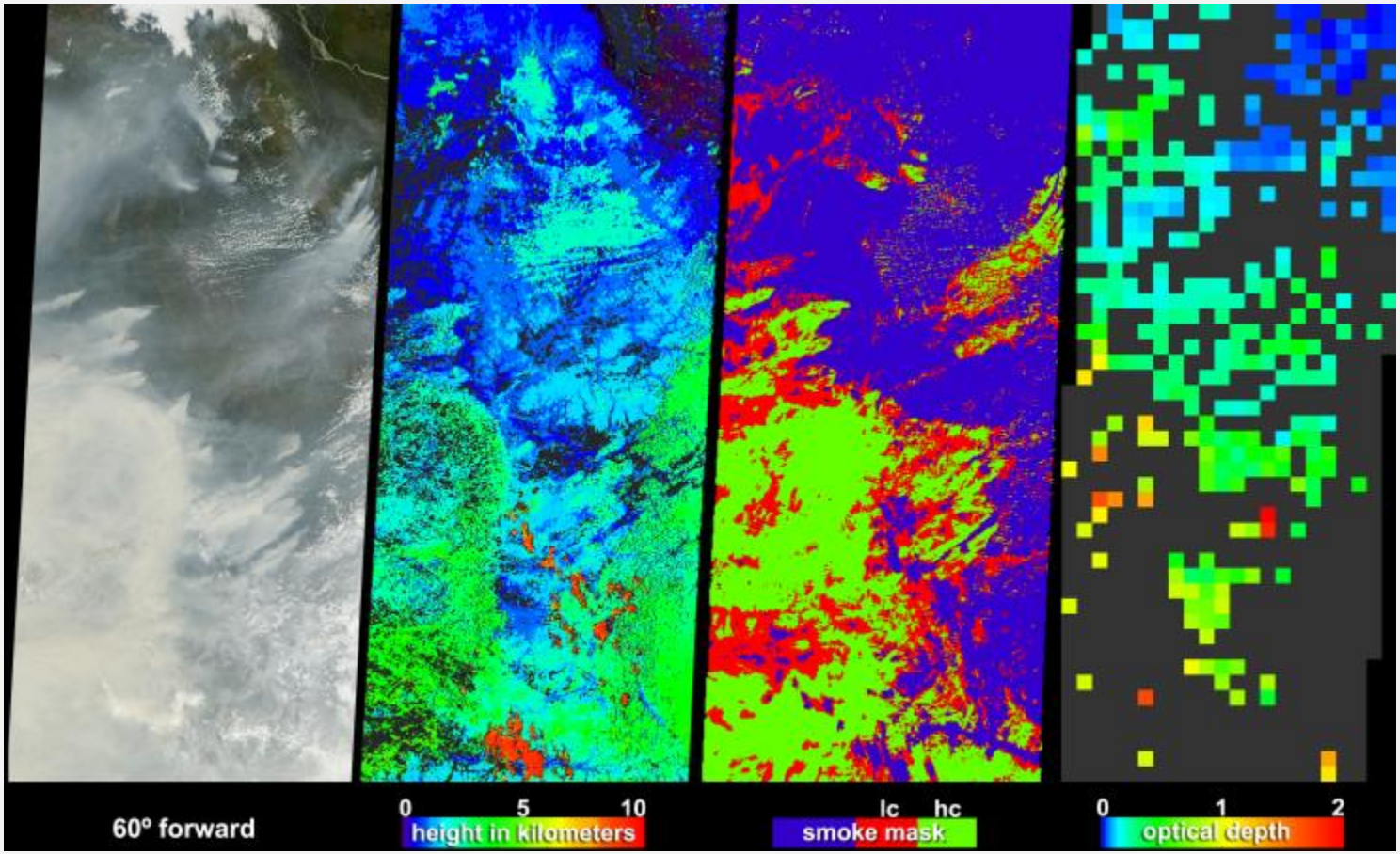
Angular observations (which are not available in MODIS) makes MISR capable of providing additional information on particle size, shape and aerosol height under specific cases

MISR Global Daily Coverage



Applications of MISR Data

Smoke signals from the July 2004 Alaska and Yukon Fires




VIIRS

Visible Infrared Imaging Radiometer (VIIRS)

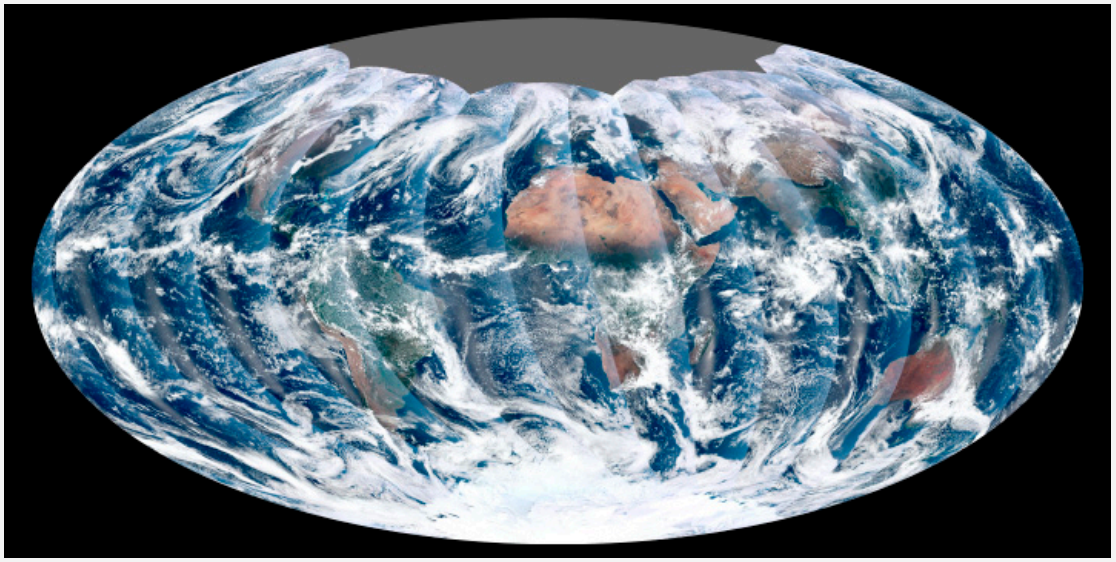
A multi-wavelength imager like MODIS with similar wavelength bands

	MODIS	VIIRS
Orbit Altitude	690 km	824 km
Equator Crossing Time	13:30 LT	13:30 LT
Granule Size	5 min	86 sec
Swath	2,330 km	3,000 km
Pixel Nadir	0.5 km	0.75 km
Pixel Edge	2 km	1.5 km

VIIRS & MODIS

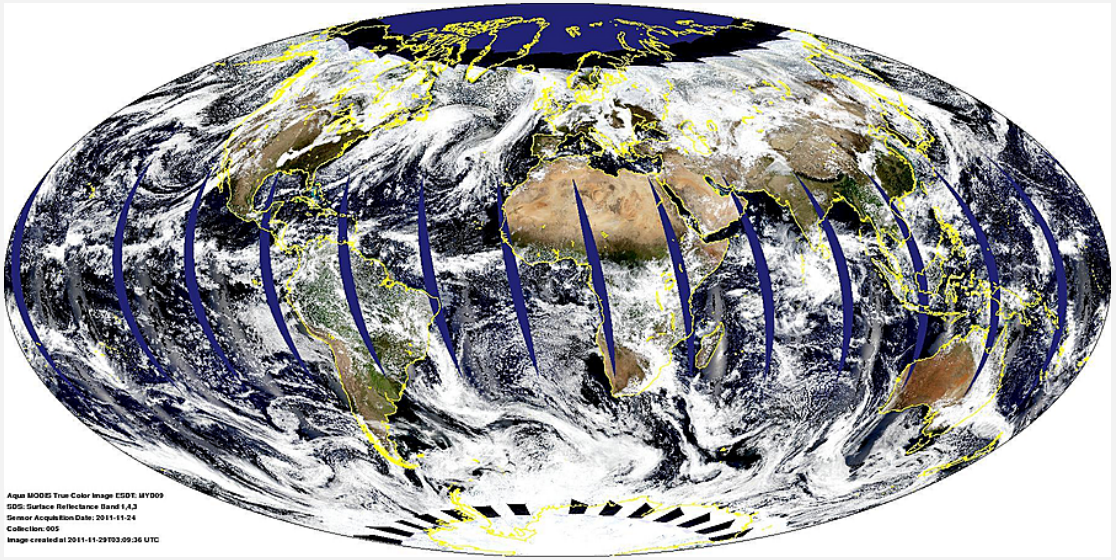
VIIRS

Nov 24, 2011



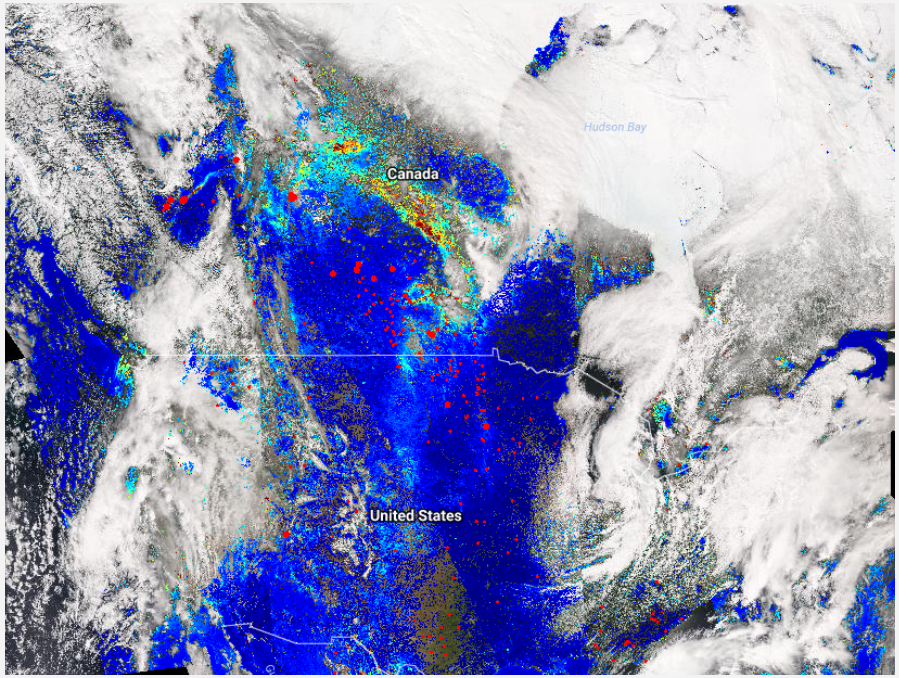
MODIS (Aqua)

Nov 24, 2011



VIIRS Level 2 & 3 Aerosol Data

- Level 2, VIIRS Data
  - http://www.class.ngdc.noaa.gov/saa/products/search?sub_id=0&datatype_family=VIIRS&submit.x=26&submit.y=6
- Level 3, Quarter Degree Gridded VIIRS Data
  - http://www.star.nesdis.noaa.gov/smcd/emb/viirs_aerosol/products_gridded.php



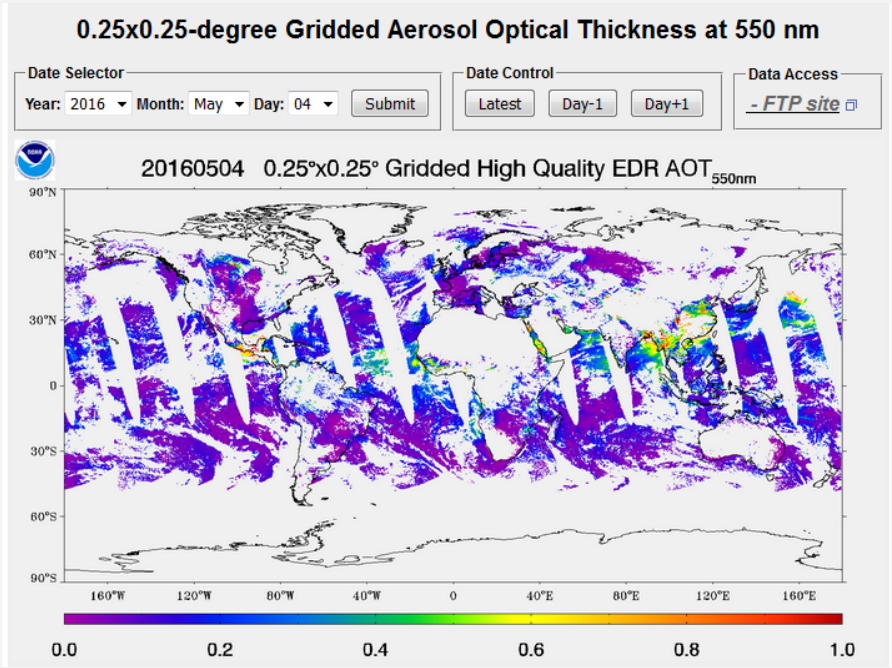
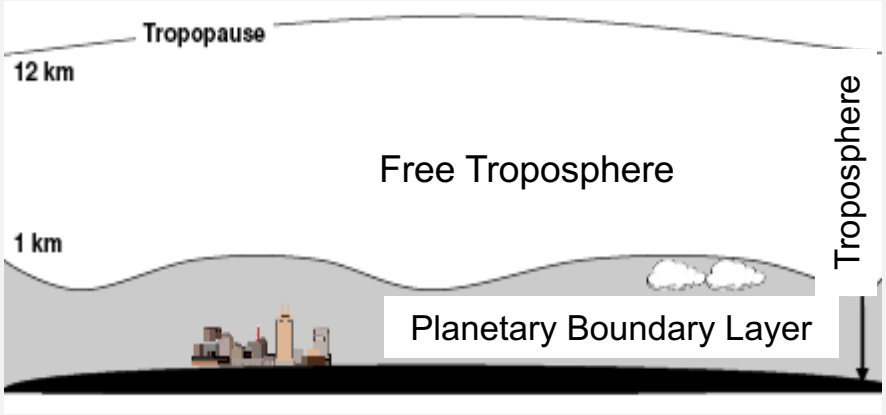
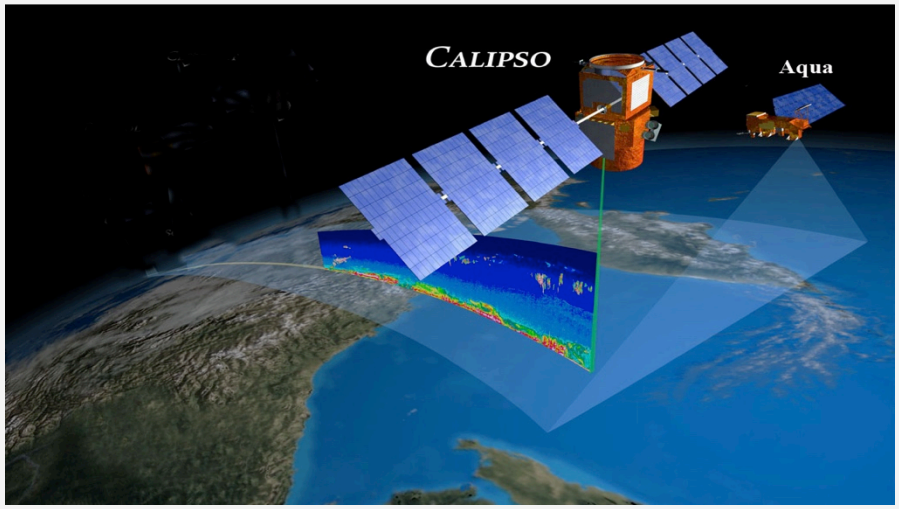
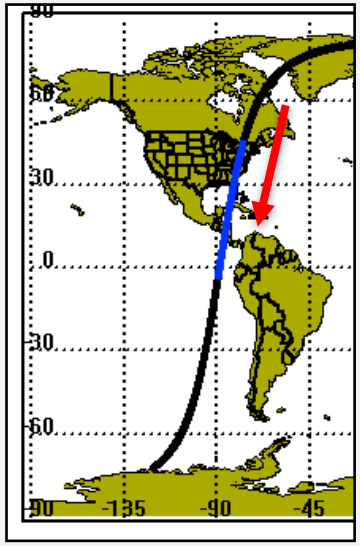


Image: http://www.star.nesdis.noaa.gov/smcd/spb/aq/eidea/

CALIPSO: Vertical Profiles

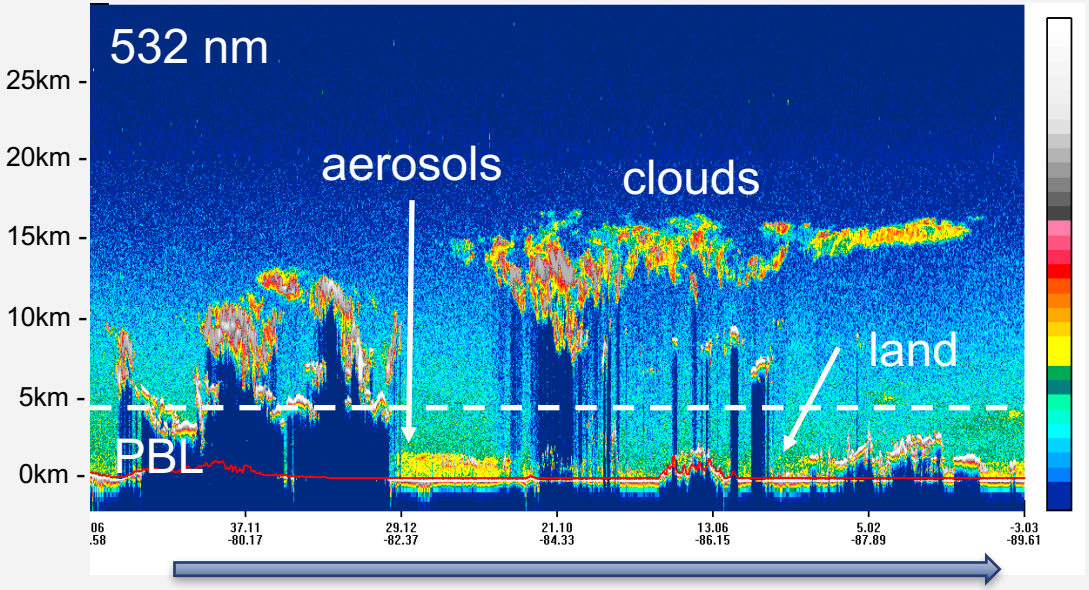






Latitude

Longitude



Source: Meloë Kacenelenbogen

Available Satellites for Aerosol Monitoring

	Pros	Cons
MODIS	• High spatial resolution (0.25-1km) • Fine vs. coarse • Twice daily near-global coverage	• No data under cloudy conditions • No vertical information • Larger uncertainties over bright targets
MISR	• Size/shape information • Higher accuracy • Multi-angle view	• Limited swath width (360km) • Limited vertical information • No daily observations for air quality
OMI	• Daily near-global coverage • Absorbing aerosols • Precursor measurements (sulfate, nox) • Available over bright targets	• Lack of information on scattering aerosols • Coarse resolution to separate clouds • Larger uncertainties
POLDER	• Daily near-global coverage • Sensitive to small mode aerosols • Available over bright targets	• No data under cloudy conditions • No vertical information • Larger uncertainties over bright targets
CALIPSO	• Vertical information available • Information on clouds	• Narrow swath (almost point measurement) • Very limited global coverage • Larger uncertainties in retrieved data sets

VIIRS, HIMAWARI, GOCI, and many more

Satellite Limitations

- **Optical measurements**
  - Only available in day time
  - Very limited in night time
- **Only available under**
  - Cloud free conditions
  - Snow/Ice free conditions
- **Accuracy - vary (AOD) – Depends on satellite/algorithm**
  - Very good over dark vegetated surfaces
  - Moderate over urban surfaces
  - Moderate to low over bright surface
  - Complex topography (i.e. mountains) – can be problematic
  - More uncertain for complex mixture of aerosols
- **Chemical Composition**
  - Very limited capabilities, only at research level
- **Temporal Coverage**
  - Usually once a day
  - But can use multiple satellite to get 2-3 a day
  - Geostationary will provide more frequent observations
- **Spatial Resolution**
  - 10 km (good)
  - 3 km (moderate)
  - 1km, 0.75 km etc.


Questions & Discussion

References & Links

- ARSET air quality page
  - http://arset.gsfc.nasa.gov/airquality
- NASA air quality
  - http://airquality.gsfc.nasa.gov
- MODIS Atmos
  - http://modis-atmos.gsfc.nasa.gov/
- MISR data
  - https://eosweb.larc.nasa.gov/PRODOCS/misr/Quality_Summaries/L2_AS_Products.html
- OMI data
  - http://disc.sci.gsfc.nasa.gov/Aura/data-holdings/OMI
- IDEA:
  - http://www.star.nesdis.noaa.gov/smcd/spb/aq/
- Smog blog:
  - http://alg.umbc.edu/usaq/